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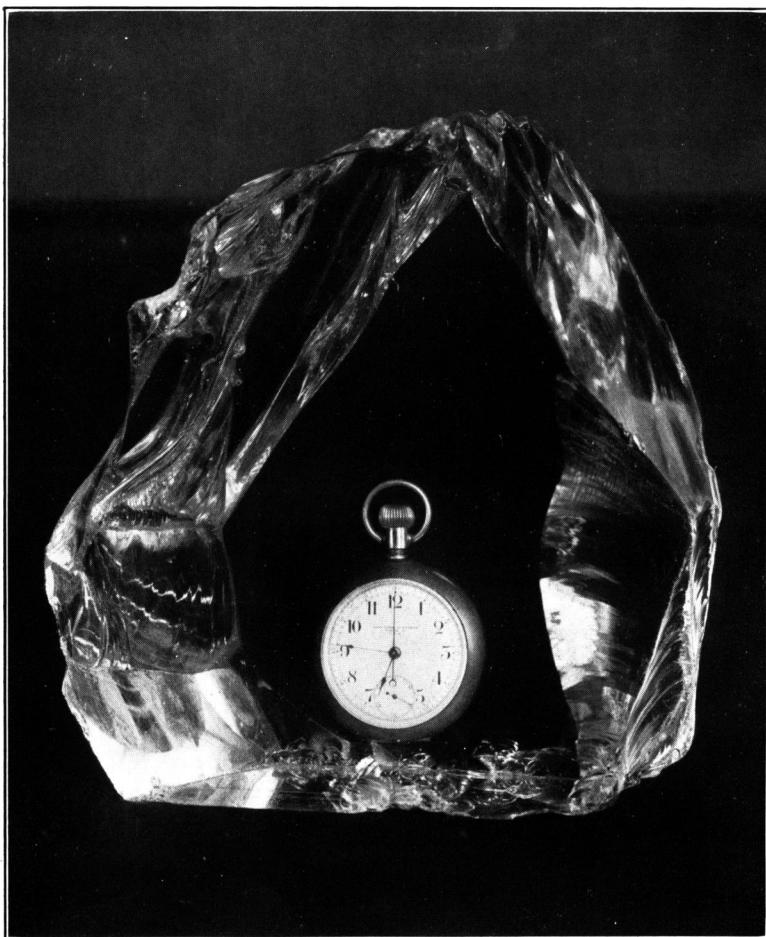


PLATE IV. A 13-pound piece of medium flint optical glass, made by the Pittsburgh Laboratory of the Bureau of Standards. Two faces have been polished for inspection; the watch is seen thru four inches of glass.

OPTICAL GLASS
By HEBER D. CURTIS

The astronomer, whether professional or amateur, is apt to have a rather vague idea of the extent to which optical glass is used outside of the lenses and prisms of his own instruments. Most amateurs know that two sorts of optical glass, crown and flint, are needed for their telescope objectives, and have read of the difficulties inherent in securing disks of a size and perfection adequate for the lenses of giant telescopes. It may be mentioned here that nineteen failures were experienced before the disk for the flint lens was obtained for the objective of the Lick 36-inch refractor.

The point which many do not adequately appreciate is the fact that the telescope lens, while the most difficult to obtain in the larger sizes, is one of the least of the modern applications of optical glass. Every binocular, every camera, every microscope, or any other instrument of precision thru which light must pass, requires its quota of a substance which differs from ordinary glass almost as much as does the diamond from graphite; both of the latter are carbon, and the optical and the ordinary sorts are both glass, but there the resemblance ends.

When we pass from the needs of peace to the requirements of a nation waging modern scientific war, optical glass changes from a mere essential of the observatory or the laboratory to an element nearly as indispensable as the high explosive. Binoculars, and excellent ones, are needed in vast numbers in all branches of the military service. It would not be advisable, even with peace at last assured, to state the enormous number of high-grade binoculars which were being made every week at the time of the signing of the armistice. These, in turn, formed but a small part of the total consumption of optical glass for war purposes. The number and the complexity of the optical devices in use on a modern dreadnaught would surprise a physicist. The army requires an equally bewildering array. Gun sights, bore-sighting devices, tank sights, range-finders, periscopes, bombing sights, airplane cameras, and many other types of optical instruments requiring lenses and prisms of high optical quality, are needed for war, not by scores, but by thousands and tens of thousands.

Prior to August, 1914, practically all our optical glass came from a few German, English and French makers. There were some secrets in the industry, but the total annual world demand amounted to only a hundred tons or so. No American firms had cared to go to the expense involved in satisfying this demand, which is relatively very small, from the standpoint of the tonnage of the commercial glass manufacturer. One large optical firm had started to make optical glass for its own use.

The war at once cut off the German supply, and practically all the English and French product was requisitioned by these nations for their own extensive military needs. The United States had been absolutely dependent upon these foreign sources of supply, and our government found itself suddenly faced by the necessity of creating its own optical glass industry. The same conditions existed in many other lines where the war later found us entirely unprepared. Before we could furnish any glass for the needs of science and industry, we must first make the glass.

That the cutting off of the supply of optical glass threatened to have very serious consequences was at once recognized by many. Several manufacturers started work on the problem. The Bureau of Standards at once began research work in this field, setting up its experimental furnace and auxiliary apparatus in its Pittsburgh plant in the winter of 1914. This experimental work was pushed vigorously, and the Bureau installed its first one thousand pound pot in the winter of 1916. It is found difficult to "experiment" on proportions and ingredients when only small amounts are melted; something can be told as to the nature of the product, but the deductions as to the actual value and quality of the glass are apt to be at fault.

This pioneer work proved of great value. We must first understand, however, something more of the manufacture of optical glass, in order that we may realize certain of the difficulties of the problem. I shall reserve for the last portion of this paper a brief résumé of the various sorts of optical glass.

Optical glass is not easy to make. The ingredients, carefully selected as regards purity, properly ground and mixed, are melted in large pots holding from five hundred to a thousand pounds or more. The furnace temperature must be very carefully controlled; if too low, the bubbles will not rise and disappear; if too high, portions of the pot will dissolve. The melted glass must be thoroly

stirred to make it as homogeneous as possible. The stirring rod itself, and some small portion of the pot wall, will melt and dissolve in the glass; hence these must not contain any substance which will color or stain the glass. When, after long and careful cooling, the fused block is cooled, and the pot is broken from around the glass, all portions near the pot wall are found to be contaminated by the pot material and worthless for optical purposes. The blocks and fragments from the central portions are then carefully inspected to determine their value. To be suitable for high-grade lenses and prisms the glass must be of high homogeneity and transparency, it must be almost completely free from small bubbles and contain no "stones," it must have very few or no "striae," and it must be free from internal strains. These exceedingly rigorous requirements bring it about that, on the average, only about twenty per cent of a very successful melt is of sufficiently high quality to render it usable. The satisfactory blocks and fragments from the central portions of the pot will be worth from four to six dollars per pound, and it is doubtful whether much profit can be made at these prices. Frequently these selected rough pieces are heated almost to the melting point and pressed in moulds into convenient slabs or disks.

Many difficulties were met at the start and gradually overcome by the Bureau experts. One of these was the finding of a suitable refractory material for the pots. This was finally found in the waste bisque of white-ware potteries. It formerly took a long while to produce a pot by hand work. A method of casting the pots was developed which cut down this time to three weeks. The pot material must be practically free from any iron oxide; more than 0.02 per cent of this will tend to discolor the glass.

At the time of the declaration of war between the United States and Germany considerable progress had been made. Some success had been attained by the Bausch and Lomb Company, Keuffel and Esser, the Spencer Lens Company, and the Pittsburgh Plate Glass Company. The Bureau of Standards had made some very good glass, but its capacity was small. There was need, at once, for very much larger quantities of optical glass to meet the requirements of the army and navy, or of the optical firms who were desirous of taking contracts for the instruments needed by these services. Conferences were held, and it was realized that energetic measures must be taken at once for a great expansion of the small optical glass industry. In this work many agencies co-operated.

The Bureau of Standards at once enlarged its Pittsburgh plant, and placed at the disposal of all interested the results of its preliminary experimental work in this field. The glass manufacturers provided enlarged facilities. The Geophysical Laboratory of the Carnegie Institution sent experts to the optical glass factory of the Bureau of Standards and to the Bausch and Lomb plant, studied the methods which had been developed, and gave valuable assistance in the analysis of materials and product, the procuring of pure materials and the development of inspection methods. A valuable method for quickly testing and inspecting the rough blocks by immersion in a tank filled with liquid of the same refractive index as the glass was developed by Mr. Taylor of the Bureau of Standards' Laboratory at Pittsburgh, and is now in use by several firms. It greatly expedites the preliminary inspection of the glass, by obviating the necessity, which formerly existed, of polishing or rough-grinding surfaces to make possible the examination of the glass for striae and other defects. A very large variety of useful optical glasses is known, but it was found not only possible, but advisable in the emergency, to limit the types manufactured to a few, not more than eight or ten.

It is a pleasure to state that the emergency was successfully met, and that optical glass of excellent quality was soon being made in quantities sufficient to meet the multifarious needs of our army and navy. The total production was probably in the neighborhood of twenty tons per month. The Bureau of Standards Laboratory at Pittsburgh, running eight single-pot furnaces, had nearly reached its planned capacity of two tons of optical glass per month at the time the armistice was signed. Most of this went to the Navy Optical Shop Annex at Rochester, where the navy made its own optical parts for many of its instruments; a smaller amount was sent to the Bureau shops at Washington, where it was used for the needs of the Bureau and for various experimental purposes. The views which illustrate this article are in all cases, except the binocular striae, of optical parts made of Bureau of Standards glass.

I wish that the limits of this article and considerations of military expediency would permit a complete description of the war activities of the Bureau of Standards, of which its services to the optical glass industry form but one item. In times of peace, a busy place engaged in scientific and industrial researches nearly as numerous

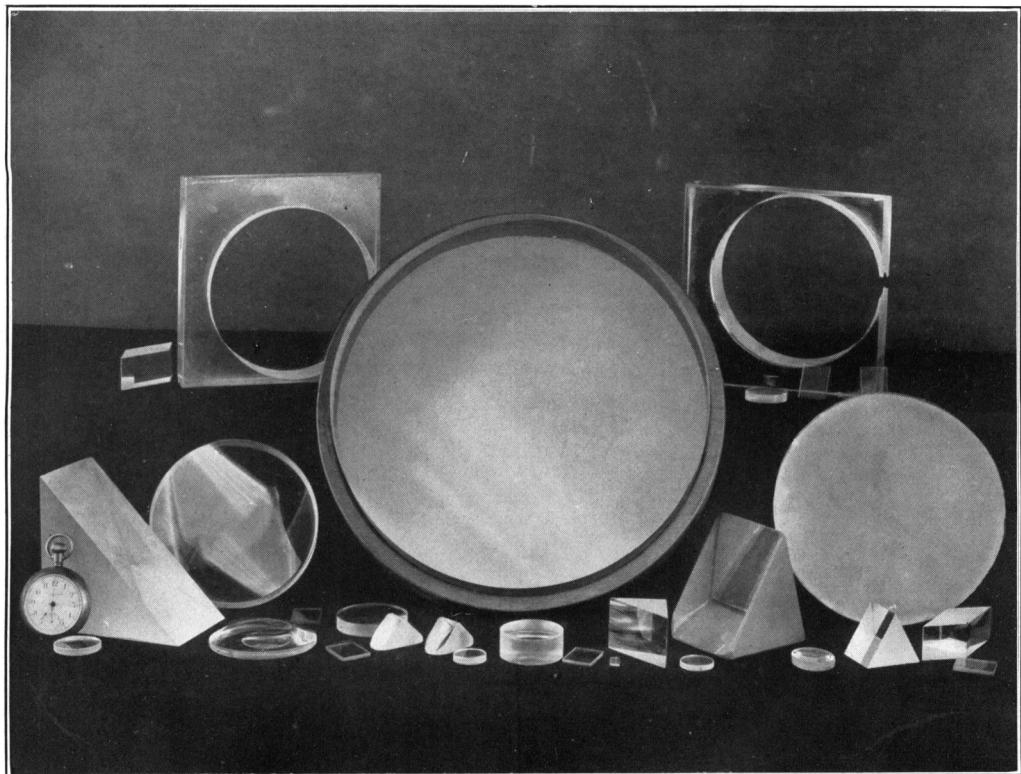


PLATE V. Finished optical parts made at the Bureau of Standards from Bureau of Standards optical glass. The 12-inch flat, the two large prisms, the 5-inch doublet of 21 inches focal length, and the sextant mirrors were made by Mr. J. Clacey, the smaller prisms and lenses by Mr. F. C. Weaver, in the Bureau of Standards Optical Shop. The two slabs from which the flint and crown lenses for the 5-inch lens were cut are seen on each side above. At the right is a rough-ground disk for a 6-inch lens.

as those of the combined physical and chemical laboratories of the universities of the country; under the stress of war, the Bureau perforce expanded into a personnel of nearly fifteen hundred, gathered from all over the United States, working and experimenting in every phase of the war's scientific needs. Dyes and chemicals for industry or fundamental science, methods of making ammonia, tests of recoil of great guns, airplane-wing design and testing in the Bureau wind-tunnel, tests of airplane and balloon fabrics and varnishes, tests of airplane motors (including, of course, the Liberty motor), improvements in aerial photography, design and testing of optical and other military instruments, testing of airplane instruments for recording height and speed, radio telegraphy and telephony, rating of time-pieces for the newly created merchant marine, assistance in the design of experimental apparatus for the army and navy—all these and many similar problems were attacked with success.

Glass, and especially optical glass, is a very complex material. Below are given the analyses of four optical glasses made by the Bureau of Standards; the first corresponds to the older ordinary flint, the last three belong to the "newer" types of glass containing boron and barium.

Substance	Dense Flint	Ordinary Crown	Boro.-sil. Crown	Barium Crown
SiO ₂ (Silica).....	39.0%	67.0%	64.2%	53.6%
Na ₂ O (Sodium monoxide).....	3.0	12.0	9.4	1.7
K ₂ O (Potash).....	4.0	5.0	8.3	8.3
B ₂ O ₃ (Boron trioxide).....	....	3.5	11.0	2.7
BaO (Barium oxide).....	....	10.6	6.1	14.3
ZnO (Zinc oxide).....	....	1.5	....	2.5
As ₂ O ₃ (Arsenic trioxide).....	....	0.4	0.4	....
CaO (Calcium oxide).....	4.0	....	1.0	....
PbO (Lead oxide).....	49.0	....	....	16.7

The revised list of Jena optical glasses given in Hovestadt¹ comprises sixty-eight varieties. The amateur may ask—Why are there different kinds of optical glass, and why are so many sorts needed?

The answer to this question takes us into the realm of geometrical optics, and, to be treated with any completeness, would involve more technicalities than would be permissible in a popular article. A very brief outline of the application of optical glass in lens design will, however, be of interest.

¹Hovestadt, "Jena Glass and its Scientific and Industrial Applications," translated by J. D. and A. Everett.

A lens is a piece of glass (sometimes of other transparent substances) bounded by spherical or very nearly spherical surfaces. Light is bent from its initial direction, or refracted, when it passes the boundary surface between two media of different composition. The measure of this bending, known as the index of refraction, is defined mathematically as the ratio of the sines of the angles which the ray of light makes with a perpendicular to the refracting surface before and after passing the surface. The reason for the refraction is that light passes thru different media at different speeds; it is really the ratio of the speed of light in air to that in the glass which is given by this quantity, the refractive index. The refractive index differs for different sorts of glass, and in the same glass it varies with the wave-length or color of the light; blue light is refracted or bent more than red light.

In a camera, telescope, or similar optical instrument, we would like to have a lens or combination of lenses which would unite every ray, of every color, proceeding from a given point of the object, precisely into the corresponding point of the image. It can be proven mathematically that there is no lens, nor any possible combination of lenses or shapes of lens surfaces which will do this with *absolute* accuracy. It is the aim of the lens designer, however, to attempt to get as close to the desired perfection as he can by properly proportioning the curves of his lenses, their respective thicknesses, the distances between the different lenses, and the refractive powers of the sorts of glass used.

While much can be found out as to the magnitude of the various errors or aberrations of a lens system, in a general way, by mathematical analysis, the final proportions of a compound lens of high quality are to be found only by "cut and try" methods in the optical shop, or by tedious trigonometrical calculations. In these calculations the lens designer traces the paths of different rays, of different colors, thru all the surfaces of a lens system, and determines how well the rays from a point of the object can be united in the corresponding point of the image. If the performance is not satisfactory, some or all of the dimensions of the lens system are varied, and the rays traced thru again.

"At first sight it seems a remarkable thing that a system of surfaces bound by the simplest of all known curves, namely, the circle, with their centers on a common axis, should give rise to problems which, *if solved to a high degree of exactitude*, are of such extraordinary complexity."—(Taylor, *A System of Applied Optics*, page 5).

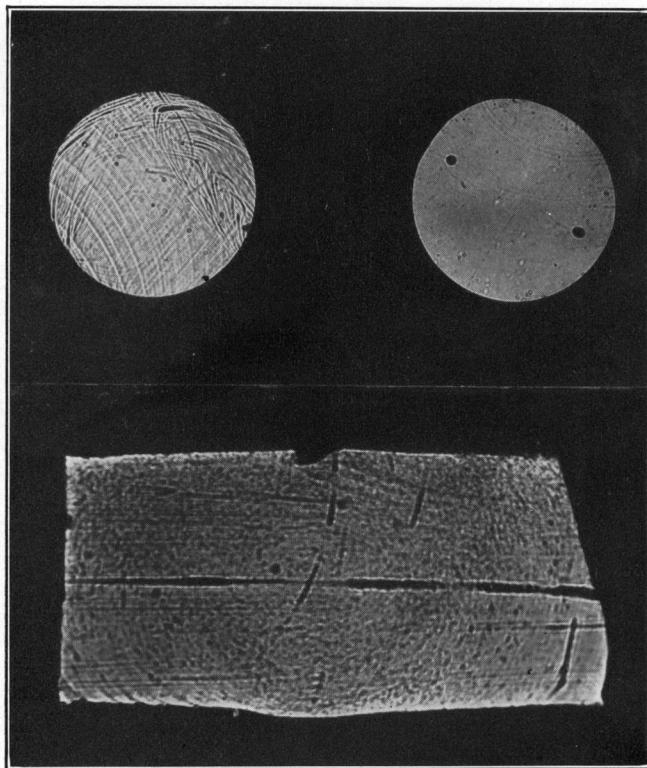


PLATE VI. Striae in a piece of optical glass and in the lenses
of a binocular.

A reasonably perfect modern camera lens is generally the work of many men, both as to the design and the manufacture. It is said that merely the design of the first Zeiss Tessar camera lens involved months of work by four skilled and many routine computers, and cost in the neighborhood of 30,000 marks.

Your camera lens, then, is not a simple shape of one sort of optical glass. It consists of from four to eight carefully shaped and proportioned lenses, composed of at least two sorts of optical glass. A good microscope objective will frequently have as many as ten separate small lenses, of different glasses and curvatures, some of which are cemented together and others not.

A *single* lens with spherical bounding surfaces will be of very limited usefulness as a telescope or camera lens. It will be afflicted with spherical aberration (light from different zones of the lens fails to come to a single focus); chromatic aberration (light of different colors will not come to the same focus); astigmatism (horizontal and vertical lines off the axis can not be brought to the same focus); coma (rays making an angle with the axis will meet in a comet-like image instead of in a point); and other errors. If the focal length be very great compared with the aperture of the lens, and the field of view small, most of these errors will not be very noticeable, and for this reason many of the earliest telescopes were made very long.

If now, for a telescope objective, we combine two lenses, one of crown glass (refractive index usually from 1.50 to 1.55), and one of flint glass (generally characterized by containing lead oxide, and having refractive indices from 1.56 to 1.65 or higher), many of these errors, notably the chromatic aberration, can be greatly reduced. In particular, with the older sorts of flint and crown glasses, we can make a telescope lens which will bring to the same focus two different colors of the spectrum, thus getting rid of a good deal of the chromatic aberration. If we choose the two colors for which we correct the objective in the green and the yellow, the visual region, we shall have a very good telescope lens, tho there will be a fringe of purple around the edges of bright objects, due to the neglected red and violet rays. This peripheral color effect troubles the astronomer very little. However, the first thing which the average visitor says on looking thru the Lick telescope at some bright object like *Jupiter* is—"What a beautiful purple color!" and is at some pains to comprehend the attendant astronomer's

explanation that this color does not belong to the planet at all, but is an effect due to the telescope itself.

There is actually more than three inches between the points where the yellow and the violet rays are brought to their foci in the Lick refractor.

Up to about 1888 the optician had only the usual crown and flint glasses at his disposal. It was at this time that the experiments of the Schotts, with the assistance of the firm of Zeiss and liberal subventions from the German government, resulted in the discovery of new types of glass which have made possible great improvements in lens design. Too much credit can scarcely be given these investigators for these improvements.

In addition to the six elements occurring in the older types of optical glass, namely, silicon, potassium, sodium, lead, calcium, and oxygen, the Schotts tried twenty-eight other elements in varying proportions up to at least ten per cent of the whole. Of these new ingredients, which were tested in varying proportions and in many experimental melts, boron and barium proved perhaps of the greatest importance. In addition to the refractive index of a glass, there is a quantity known as its "dispersion," or the relation existing between the refractive indices of the glass for different colors, which is of the highest importance in removing or diminishing the many aberrations to which a system of lenses is subject. This dispersion factor is ordinarily indicated by the Greek letter ν , and is defined by the formula:

$$\frac{n_D - 1}{n_F - n_C} = \nu$$

In the above formula

n_D = refractive index for light of wave-length 5893

n_F = " " " " " 4862

n_C = " " " " " 6563

In the older glasses this factor decreased with the increase in the refractive index in different glasses; in the "new" optical glasses the values of this dispersion factor for the flints and crowns are made more nearly equal. A few typical values are given here.

Glass	n_D	ν
B. of S. Very Dense Flint ("old").....	1.6555	34.4
B. of S. Ordinary Crown ("old").....	1.5171	59.6
Jena Borosil. Flint ("new").....	1.5676	46.4
B. of S. Barium Crown ("new").....	1.6176	55.1

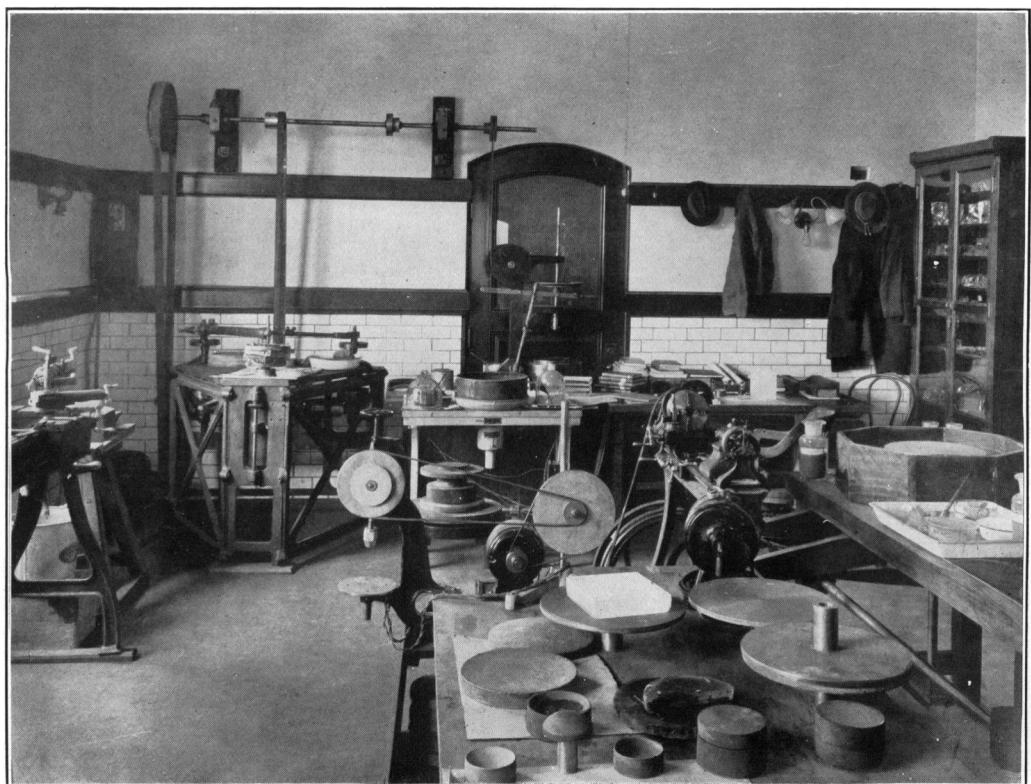


PLATE VII. A view of a portion of the Optical Shop of the Bureau of Standards.

This peculiarity of the dispersions of the "new" or Jena glasses has made possible the correction of the chromatic aberration of a telescope lens for *three* separate colors, instead of for *two* colors, as with the older types of glasses, and has thus greatly reduced the amount of uncorrected color in such objectives. They have also proved of very great value in the design of modern photographic lenses.

Previous to the outbreak of the European war, later to become a world war, the optical glass industry was entirely European. We have sketched, necessarily in briefest outline, the work which has been done to bring this into the category of American industries. There is still a wide field for further experimentation, and the Bureau of Standards will certainly continue this phase of its activities.

What of the future of this industry in the United States? Here commercial and financial considerations will undoubtedly prove of paramount importance. At least two of the firms at present manufacturing optical glass propose to continue in the field; several others, which have engaged in the work to assist in meeting war needs, will cease manufacture soon. There is little profit in this product, and some patriotism will have to be combined with the profit or loss of the balance sheet. It is not, and never will be, a very large industry, important as it is for the scientific independence of the country. We are making in America as good optical glass as that of any foreign firm. Can those firms which will continue in the production of American optical glass meet the post-war competition of foreign cheaper production? This is a matter for the earnest consideration of those who desire to see this country self-contained and independent in this essential and important industry. It appears certain that this country should never again be permitted to become entirely dependent upon foreign optical glass; we can and will make our own.